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DOE NHI: Progress in Nuclear Connection Technologies

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DOE NHI: PROGRESS IN NUCLEAR CONNECTION TECHNOLOGIES

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Abstract – The U.S. Department of Energy Nuclear Hydrogen Initiative (NHI) is seeking to develop the technologies to enable the large-scale production of hydrogen from water using a nuclear powered heat source. A necessary component in any nuclear powered hydrogen production process is the energy transfer connection between the nuclear plant and the hydrogen plant. *This article provides an overview of the research and development work that has been accomplished on the high-temperature heat transfer connection between the nuclear power plant and the hydrogen production plant by the NHI. A description of future work is also provided.*

I. INTRODUCTION

The U.S. Department of Energy (DOE) Nuclear Hydrogen Initiative (NHI) is tasked with developing the technologies to enable the large-scale production of hydrogen from water using nuclear power. Though conventional liquid water electrolysis can be used today in combination with electricity provided from a light-water reactor (LWR) or boiling water reactor (BWR) to produce hydrogen, the NHI is seeking to develop more advanced hydrogen production methods that would be able to split water with greater efficiency and at lower per-unit cost. In the hydrogen production processes under consideration – the Sulfur-Iodine Process [1], the Hybrid Sulfur Process [2], High-Temperature Electrolysis [3], and others – water is the source of hydrogen and no fossil fuels are consumed. Oxygen is produced as a by-product.

All of the hydrogen production processes under study by the NHI use high temperature thermal energy (> 900 K) to offset some or all of the electrical energy needed to decompose water into its constituents, as compared to liquid water electrolysis. The use of thermal energy to perform this task instead of electrical energy is desired because thermal energy can be used directly without first having to convert it into electricity, a conversion step that costs energy. The source of high-temperature thermal energy is envisioned to be a Very High Temperature Gas-Cooled [nuclear] Reactor (VHTR), and the combined nuclear plant/hydrogen plant facility is known as the Next Generation Nuclear Plant (NGNP). Figure 1 shows a schematic of the proposed NGNP facility. The VHTR is one of six Generation IV nuclear reactor concepts [4].

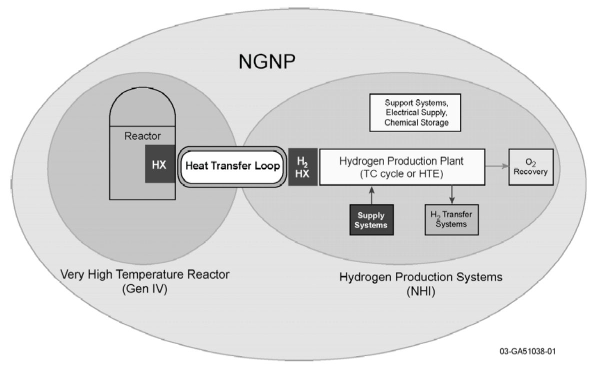

Figure 1. Schematic of NGNP Facility

A necessary part of the NGNP is the high-temperature thermal connection between the nuclear plant and the hydrogen production plant. This thermal connection is also known as the intermediate heat transfer loop. The intermediate heat transfer loop must be capable of receiving high-temperature thermal energy from the VHTR and transmitting it over long distances (10's to 100's of meters) to the hydrogen production plant. The intermediate loop is composed of an intermediate heat exchanger (receiving heat exchanger), high temperature fluid pipes and fluid motivators, and at least one hydrogen process heat exchanger (transmitting heat exchanger).

The NHI is performing research and development to enable the construction and operation of the intermediate heat transfer loop in support of the NGNP. The research areas of interest include materials and fluids, heat exchanger design, integrated system modeling, and safety. Snapshots of the work that has been accomplished in these areas are provided in this article, and plans for future research and development activities are described.

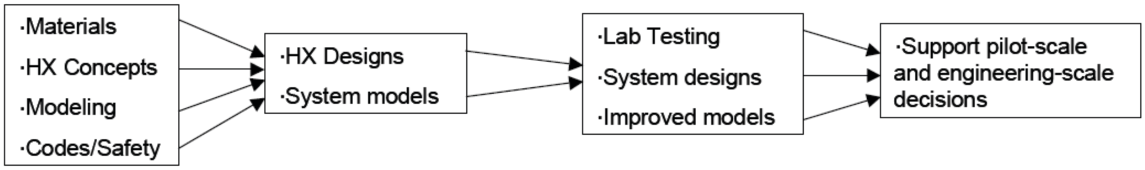

Figure 2. NHI development pathways for Intermediate Heat Transfer Loop

II. AREAS OF RESEARCH

Research and development work on the intermediate heat transfer loop is proceeding along separate but convergent pathways. These pathways are shown in Figure 2. The pathways are materials (structural and fluid), heat exchanger designs, integrated system modeling, and codes and safety. As information is collected in these areas, more detailed heat exchanger and system designs can be generated. Once detailed design decisions are made, lab-scale testing is performed on heat exchangers and other equipment, and data collected from those tests is incorporated into improved integrated models. This information, examined collectively, will support future pilot-scale and engineering-scale decisions leading up to the construction and operation of a fully integrated commercial-scale NGNP. Progress has been made in these research areas, and the NHI is in the stage of laboratory testing and in developing more detailed system models.

II.A. Materials

The VHTR is expected to generate outlet temperatures in the range of 1100-1200 K at a pressure of up to 7 MPa [5]. At this temperature and pressure, the choices of structural materials that can be used for an intermediate heat exchanger are limited to a small subset of materials that can retain their strength at temperature. In a heat exchanger application, the heat exchanger surfaces are subject to the highest-temperature conditions, and insulating materials cannot be used to facilitate the use of more common materials of construction (e.g., copper alloys, carbon steel, 316 stainless steel). The high-strength materials under examination fall into two classes – metallic alloys, and ceramics.

High-temperature tensile testing [6] has been performed on Inconel® 617, Incoloy® 800H, Waspaloy, Hastelloy C-22 and C-276, and high-temperature tensile tests are under way on Inconel 718 and Haynes 230. This testing has been done to fill in gaps in the available literature data and to identify the best metal alloy candidates for the intermediate heat exchanger. For all the metals tested, the yield strength and ultimate strength drop precipitously above 1100 K, as indicated by the measurements for Inconel 718 in Fig. 3.

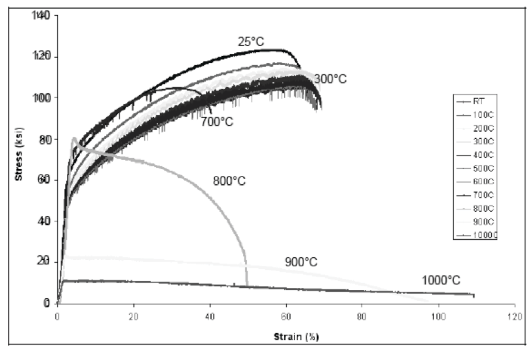

Figure 3. Tensile properties of Inconel 718 up to 1273 K

Preliminary data indicate that Inconel 617 and Haynes 230 may be the best candidate alloys for this application, and more tests are planned to measure the creep-fatigue behavior of these metals.

Microstructural analyses of failed samples were performed [6]. In most cases, failures were due to ductile failure mechanisms, but in some cases, such as for C-276 in the temperature range 973-1073 K, dynamic strain aging led to brittle failure. An SEM micrograph of a failed C-276 sample is shown in Fig. 4.

Ceramic heat exchanger materials are under consideration for the intermediate heat exchanger and for process heat exchangers. Among the commercially available ceramic materials, SiC, Si_3N_4, and Al_2O_3 appear to provide the best combination of high-temperature strength, toughness, corrosion resistance, and ease of processing. In tests, these materials were found to be very corrosion resistant to 1173 K steam and sulfuric acid for an exposure period of 1000 hours [7]. Carbon fiber reinforced C/SiC composite materials have also been investigated, and model heat exchanger plates have been manufactured and joined, as shown in Fig. 5, in order to demonstrate the feasibility of manufacturing [6].

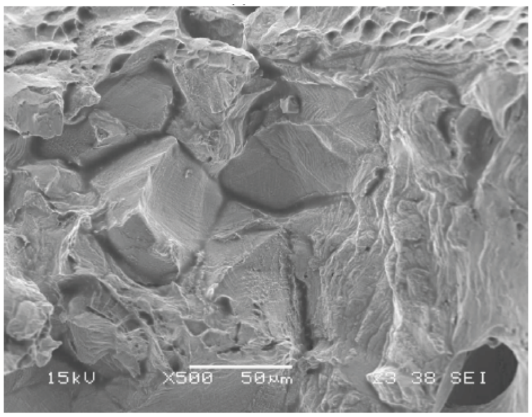

Figure 4. SEM micrograph of C-276, 500x, after failure at 973 K.

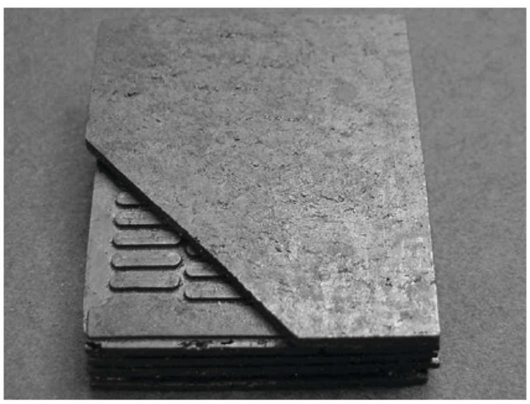
Figure 5. SiC/C composite plates manufactured using polymer infiltration and pyrolysis.

Much corrosion testing has been done to identify materials for the process side of heat exchangers that would be used for the hydrogen iodide (HI) decomposition section in the Sulfur-Iodine Process. The HI decomposition section, shown in Fig. 6, contains HI, water, iodine, and phosphoric acid, and operates at about 723 K at its highest temperature. Though the temperatures in this section are low enough to allow for the use of more common materials of construction, the chemical conditions are severe, and only select materials have been found to survive for longer than several hundred hours. Ta-2.5W, Ta-10W, and SiC have been identified for use in the iodine separation section at 413 K, and corrosion rates less than 0.0075 mm per year have been measured for these materials. For the HI gaseous decomposition section, Hastelloy B, C-22 and C-276 have been identified as good candidates and have been shown to have corrosion rates between 0.0625 and 0.338 mm per year at 723 K, as measured over a time period exceeding 1220 hours. For the phosphoric acid concentration section, corrosion testing is still underway, and so far only ceramics such as SiC and the Ta-W alloys previously examined have been found to be suitable [8].

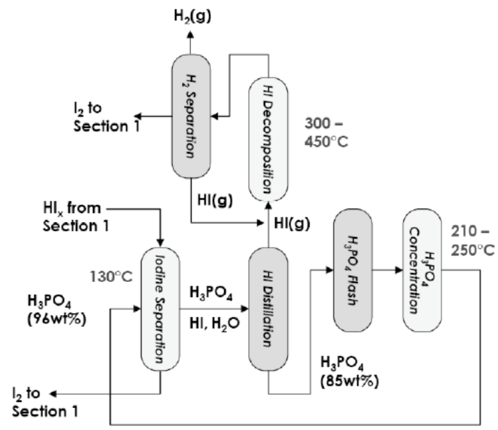

Figure 6. HI decomposition section with extractive distillation in Sulfur-Iodine Process.

Though helium is the current reference fluid for the long distance intermediate loop, there is work being done to identify suitable structural materials that are compatible with molten fluoride salts, and to understand corrosion chemistry mechanisms, particularly of FLiNaK [9]. Molten salts are favored over liquid metals for this use due to their low vapor pressures at the temperatures of interest (1100-1200 K) and their relatively low chemical reactivity with hydrogen process fluids. Past analysis has shown that the diameter of intermediate loop piping and pumping power can be greatly reduced by changing the intermediate heat transfer fluid from a compressed gas to a liquid [10].

II.B. Heat Exchanger Design

Detailed modeling of heat exchangers for the intermediate heat exchanger and the sulfuric acid decomposer is underway. The purpose of the modeling work is to understand the effects of design changes on calculated mechanical and thermal stresses and on sulfuric acid decomposition behaviors, so that effective heat exchanger prototypes may be constructed in the laboratory.

For the intermediate heat exchanger, a compact offset strip fin plate C/SiC design that employs helium in the hot channels and molten salt in the cold channels is under examination [8]. To decrease computational time, porous media approximations have been made to simplify the fluid mechanics calculations that are needed to calculate global steady state and transient temperature distributions. Information obtained from these calculations will be used to obtain more accurate estimates of localized stresses using a unit-cell analysis method [11] that separates the heat exchanger into zones and extrapolates the stresses calculated for the zonal unit cell to each zone (see Fig. 7).

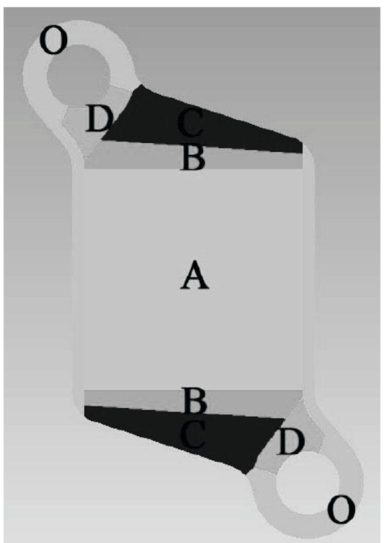

Figure 7. C/SiC plate divided into zones.

In this design, the pressure drop between the nuclear reactor (7 MPa) and the hydrogen plant (0.1 to 1 MPa) is fully absorbed by the intermediate heat exchanger. Sample heat exchanger plates have been manufactured (see *II.A.* above).

Several alternative designs for sulfuric acid decomposers are under examination [7]. These designs are classified as shell-and-tube, bayonet, and compact.

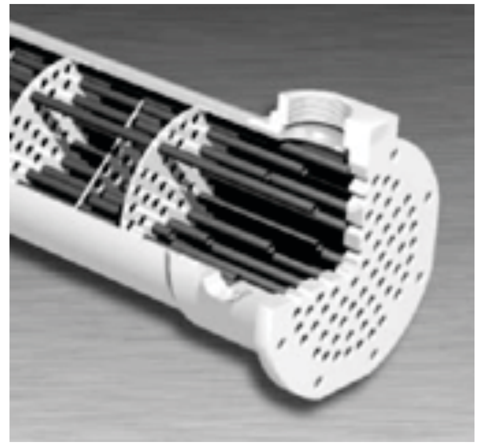

Figure 8. Shell-and-tube heat exchanger

In the shell-and-tube heat exchanger design (Fig. 8), the hot fluid from the intermediate loop flows into the shell side, and the reacting sulfuric acid/SO_3/SO_2 vapor flows through the tube side. Packed catalyst is placed in the tubes to facilitate the SO_3 decomposition step. The tubes are assumed to be SiC and the catalyst is assumed to be Pt on a TiO_2 support. Analysis of the design using finite element methods is just getting underway.

In the bayonet design, shown in Fig. 9, concentric SiC tubes containing Pt catalyst are used to perform the sulfuric acid decomposition reactions.

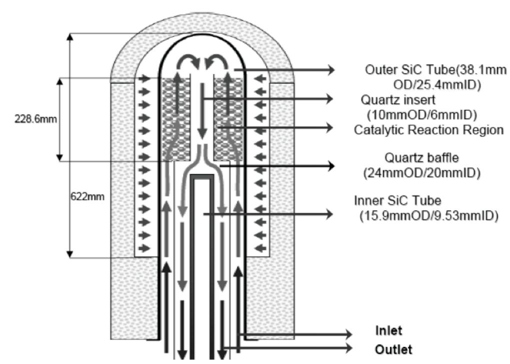

Figure 9. Bayonet H_2SO_4 decomposer design.

The inner SiC tube is open-ended, while the larger SiC tube is closed at one end. Thermal energy is transferred to the reacting section through the surface of the outer tube. Countercurrent flow of colder and hotter gases conserve energy and keep the hotter zone contained at one end of the bayonet, away from the ceramic-to-metal seals at the other end of the bayonet. Calculations are being done to understand the temperature distribution within the bayonet and to optimize the various dimensions. Laboratory tests of this design with catalyst and electrical surface heaters are underway.

The third design is a SiC compact heat exchanger that is being developed by Ceramatec, Inc. In this design (Fig. 10), Pt catalyst is assumed to be on the surfaces of the cold flow channels. Computational work on this design has involved the calculation of mechanical and thermal stresses, SO_3 conversion factors, and optimization of the flow channel dimensions and configurations (e.g., straight channel, hexagonal, "textured", etc.).

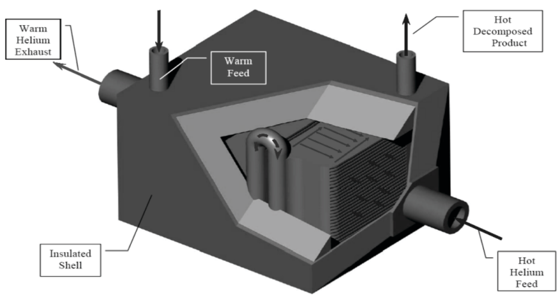

Figure 10. Ceramatec compact heat exchanger design

Laboratory experiments are also underway to measure the pressure/flow conditions in sample coupons. Sample flow coupons are shown in Fig. 11. The results obtained from tests involving water at room temperature have shown that the numerical calculations of the pressure distribution across the coupons agree with the laboratory tests to within 5% under static and dynamic configurations.

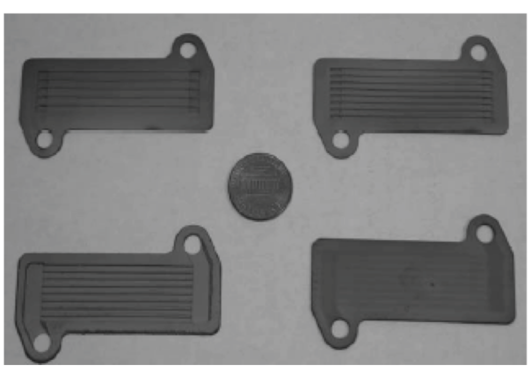

Figure 11. Sample SiC flow coupons.

II.C. Integrated System Modeling

Integrated nuclear plant/hydrogen plant steady-state models are being constructed and tested under the project heading of HyPEP (Hydrogen Plant Efficiency Program) [12]. HyPEP will be a computer program that will have the capability to model and calculate the overall energy efficiencies of a VHTR that employs a Brayton or Rankine cycle to generate electricity and a high-temperature electrolysis or Sulfur-Iodine plant to generate hydrogen. The program is being developed under an International Nuclear Energy Research Initiative (I-NERI) agreement between the Idaho National Laboratory, Argonne National Laboratory, and the Ministry of Science and Technology (MOST) in the Republic of Korea. HyPEP will employ a graphical user interface and will run under a PC-Windows environment. Though models of the integrated plant can be constructed using commercially available software (e.g., ASPEN), the HyPEP source code will not be proprietary and may be used to support a future U.S. Nuclear Regulatory Commission (NRC) license application for the Next Generation Nuclear Plant. Though the NRC's responsibility is the nuclear plant, the NRC will be concerned with how the hydrogen plant affects the nuclear plant, and the HyPEP model will be able to contribute some operational and safety information towards this goal.

The HyPEP Program is in its second year of development, and benchmark energy and mass-balance flow sheets have been prepared of various integrated plant configurations using GAS-PASS/H, HYSYS, and ASPEN codes. Preliminary comparisons of these benchmarks with the HyPEP codes for some limited configurations show that HyPEP agrees with the benchmarks to within 5%.

Dynamic models of the intermediate loop are also being constructed to understand the system behavior during start-up, shutdown, and off-normal situations. Ideally, the intermediate loop could be used to dampen or delay communication of transients between plants, and accurate dynamic models are needed to understand how this might be accomplished. The dynamic models, once developed, will be used to support plant safety studies and to develop plant control strategies.

II.D. Codes and Safety

One of the key engineering decisions that must be made in regard to the intermediate heat transfer loop is to determine how long the loop must extend from the nuclear plant. Heat losses and pumping power are minimized by making the intermediate heat transfer loop as short as possible, but placing the hydrogen plant too close to the nuclear plant may threaten the nuclear plant in the event of a hydrogen explosion or toxic chemical release. Safety must be balanced with energy efficiency to arrive at the best loop length.

Initial steps have been made to identify the minimum acceptable intermediate loop length in a recent study that employed the tools of probabilistic risk analysis (PRA), hydrogen explosion calculations, and chemical dispersion models [13]. In this study, the reference design was a VHTR reactor connected to a Sulfur-Iodine hydrogen production plant. It was determined that the effects of hydrogen explosion are dominant over the effects of toxic chemical releases in determining minimum plant spacing, and that the minimum recommended distance of the intermediate loop is approximately 110 meters to protect against hydrogen explosions involving up to 100 kg of hydrogen. The intermediate loop length may be shortened to as short as 60 maters if hydrogen blast mitigation measures are taken, such as the construction of an earthen wall or blast barrier between the two plants (see Fig. 12).

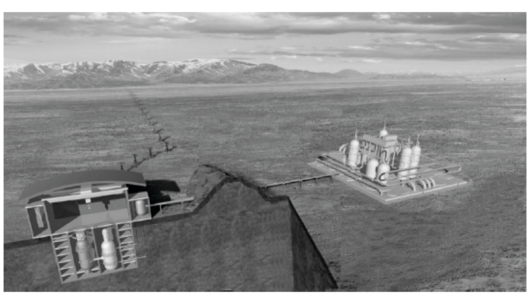

Figure 12. Earthen wall may help reduce separation distance.

Related to safety is the understanding of which codes and standards apply to the construction and operation of a combined facility. Codes and standards arise from various governing and advisory bodies and are written to help increase reliability and safety. The Next Generation Nuclear Plant will exist in the nuclear and non-nuclear domains, and will have to take into account a wider range of codes and standards than similar stand-alone facilities. A first effort has been made to define a catalog of applicable codes and standards [14], but more work will need to be done in this area as detailed facility designs are generated.

III. FUTURE WORK

Overall, future work will continue down the convergent pathways shown in Figure 2. The development work at this point is driving towards laboratory testing of prototypes and model verification.

In the area of structural materials, work will be concentrated on a subset of high-temperature alloys – most likely Inconel 617 and Haynes 230 – in order to collect more detailed information in support of ASME code certification. Mechanical data measurements, the study of fatigue and cracking mechanisms, and collection of manufacturing information will continue on SiC, Si_3N_4, Al_2O_3, and C/SiC composites in support of ceramic heat exchanger development. Within one to three years a reference intermediate heat transfer fluid will be chosen for the NGNP, but, regardless of the choice of fluid, research in molten salts will be continued due to the long-term potential for significant capital and operating cost savings. Corrosion testing will continue but emphasis will be placed on the testing of Ta-2.5W and Ta-10W clad materials in HI environments, as Ta is a very expensive metal and the costs of making large-scale equipment out of this material may be prohibitive.

Detailed modeling of heat exchanger concepts will be performed in support of developing detailed heat exchanger designs and the construction of laboratory prototypes. The SiC bayonet for sulfuric decomposition is already undergoing testing, and other concepts may be tested too in order to identify the best candidate for the pilot-scale and larger-scale plants. Testing of intermediate heat exchanger designs will be performed under simulated flow conditions and, if possible, at actual operating temperatures and pressures.

Work will continue for the next year on integrated plant models, including HyPEP. Transient modeling capabilities will be fully developed in this time frame, and work will start on examining the transient behaviors that occur during start-up, shutdown, and off-normal events. This information will be used to inform revised quantitative risk analyses of the combined plant.

The NHI is becoming more tightly aligned with the Next Generation Nuclear Plan Project, and technical work will become increasingly coordinated. Research and development tasks between the two programs will be shared for the intermediate heat transfer loop, and the NHI work on integrated plant models and safety will be used to support any future NGNP license application to the NRC.

IV. SUMMARY

The DOE Nuclear Hydrogen Initiative is performing research and development on the nuclear connection between the nuclear plant and the hydrogen production plant that will form the Next Generation Nuclear Plant. Work is proceeding along the lines of materials, heat exchanger designs, integrated system modeling, and codes and safety. Progress has been made in many areas, and development activities are now converging on the testing of laboratory prototypes and the preparation of system safety information in support of future U.S. Nuclear Regulatory Commission licensing activities. All future work will be coordinated with a companion research and development program, the NGNP Project.

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